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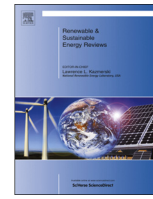

Optimal economic planning of power transmission lines: A review

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In this study an attempt has been made to present the state of the art review on the research work conceded in the areas of design, modeling and cost optimization aspects of power transmission lines. Power transmission utilities in the present days are more dependent on the standard designs for constructing transmission to minimize the capital cost. Economic studies indicate that transmission lines employing optimized designs and scientific cost management methodologies for construction are significant in achieving much higher savings in capital investments. The design and cost optimization of transmission lines is a complex aspect as various simultaneously interacting parameters are involved. Development of comprehensive cost models involving design parameters affecting the cost are required for modeling and cost optimization studies. The present study aims to review the broad areas of transmission line design and construction aspects; current status and trends in power transmission; challenges involved in construction, operation and maintenance of these lines and possible solutions for mitigating the challenges; methods applied for carrying out design and optimization studies; and finally, procedures adopted for economic analysis of transmission lines. An attempt has also been made to compare the various techniques applied for transmission line optimization studies and economic analysis methods.

Contents

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1. Introduction

Global electricity demand is expected to be doubled by 2030, growing at an annual rate of 2.4%. This growth is more in developing countries, where electricity demand will rise by over 4% per year. The share of global electricity demand in developing countries may rise from 27% in 2000 to 43% in 2030 [1]. Facing the challenge of high global electricity demand, various ways including renewable energy utilization and energy efficient technologies have been adopted for different kinds of applications [2–11]. The high electricity demand calls for high capital investments for the development of power sector infrastructure. To meet this growth in energy demand, capital investments required for the development of power sector infrastructure are expected to be $11 trillion globally and $5 trillion in developing countries. The average annual rate of investment is expected to increase from $450 billion in the current decade to $630 billion in the next decade [12]. Transmission and distribution (T&D) systems in the power sector play a vital role in meeting the energy needs. Even though the developing countries share in global energy demand is increasing at a rapid rate, much of this arises from the industrial energy needs. Table 1 shows the statistics regarding access to electricity, per capita consumption of electricity and T&D losses in some developing countries based on year 2011 data [13]. Lack of proper T&D infrastructure is the major cause of this phenomenon and for meeting the common man needs, the demand for electricity and capital investment in power sector, especially in T&D should be much higher than the projected values. Fig. 1 shows the investments planned in power sector with emphasis on T&D sector for the period 2000–2030. The figures indicate the commitment of developing nations in meeting the desired economic growth rates; however, investment in the transmission sector needs to be increased to meet the energy demand requirements safely and reliably [13].

Transmission lines play a vital role in the successful and stable operation of the power network. The generation and transmission capacity additions are to be planned and executed simultaneously which involve huge capital investment. Any delay in constructing new transmission lines will underutilize the generation facilities. Keeping in view the huge capital investment involved in transmission sector, the utilities are aiming to construct the transmission lines with least investment and gain maximum economic efficiency. According to the nature of the operating current, transmission lines are classified as alternating current (AC) and direct current (DC) lines. Overhead and underground classification of transmission lines is based on the type of construction. The present review concentrates on overhead alternating current power transmission lines, even though the referred methodologies and processes can also be applied to other types of transmission lines [14].

The present study aims to address the issues in optimal economic planning of power transmission lines with a detailed review on design and planning, modeling and optimization and economic analysis aspects. The paper is organized as follows. Section 2 deals with the importance of transmission lines in the power system and aspects of planning and construction. Section 3 briefly reviews about the trends observed in the development of transmission lines, challenges faced by the transmission utilities and recommendation of possible solutions for mitigating the challenges. Section 4 presents the works carried out on design and planning aspects of transmission lines. Section 5 deals with publications proposing different modeling and optimization algorithms essentially aimed at cost effective design and planning of transmission networks. Section 6 presents review on the economic analysis procedures for evaluating the overall cost of transmission lines. Finally observations and conclusions based on the bibliographic review on transmission lines state-of-art are presented.

Table 1
Electricity statistics in developing countries [13].

Country	Access to power (% of population)	Per capita consumption (kWh)	T&D losses (% of power output)
Brazil	98.7	2438	16
China	99.7	3298	6
Egypt	99.6	1743	11
India	75	684	21
Indonesia	73	680	9
Nepal	76.3	106	34
Philippines	83.3	647	11
Sri Lanka	76.6	490	12
South Africa	75.8	4694	8

2. Transmission lines

In order to meet the ever rising global demand for electrical energy, electric power industry is faced with the challenge of constructing new generating stations and transmission lines, as well as upgrading and improving its existing facilities. Most of the power is generated from conventional power stations utilizing fossil and nuclear fuels, which are probably located away from the load centers due to environmental constraints. The most convenient means of transporting electrical energy from generating stations to the load centers is the use of transmission lines.

2.1. Importance in power system

The transmission system forms the backbone of the integrated power system and operates at the highest possible system voltage.

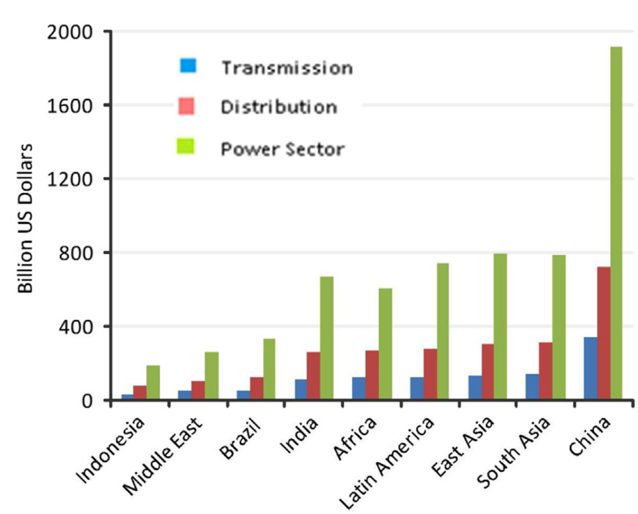

Fig. 1. Power sector investments in developing countries for the period 2000–2030 [13].

Nomenclature

$[C_D^t]$	transposed vector of cost of overload flows
$[\ \lvert P_D \rvert]$	vector of undirected overload flows
N	set of all buses
A	set of all lines
C_i	per unit generation cost
G_i	maximum generation capacity
K_j	capital cost of new line
Z_j	integer constant
F	actual system cost
$M1$	number of proposed lines
$NS(i)$	number of states of the proposed line
C_{ij}	the capital cost of proposed line
Z_{ij}	zero one integer variable assigned to proposed line
S_{ij}	linearized cost coefficient
P_{ij}	power flow
$M2$	number of existing lines
W_i	linearized cost coefficient of transmission losses
PR_i	power flow in existing lines
TC_{sys}	total cost of system consisting capital and operating costs
$Z(t)$	total generation cost/transmission losses
CF_i	fixed costs of power generation
CV_i	variable cost of power generation
$PG_i(t)$	power generation at bus i
Δt	simulation time step length
Ω	subset of branches where new investment is allowed
A	weighting factor for invest cost
$CI(X)$	total invest cost
h_{lk}	invest cost of line
M_{lk}	maximum number of new lines
t	number of time periods
I	number of buses
C^t_{invest}	transmission investment costs
C^{ti}_{gen}	generation variable cost
C^{ti}_{unser}	annual unserved energy cost
X_{ij}	power flow
$Cost_{ij}$	cost per unit power flow
N_t	number of time planning periods
P^i_0	total annual power loss
E^i	present worth of energy loss cost per unit
N_L	number of available right of ways
N^j_p	number of permitted parallel paths in available right of way
$R^i_{j,k}$	present worth of variable cost of line
$C^i_{j,k}$	present worth of installation cost of the line
$\alpha^i_{j,k}$	integer constant
$\beta^i_{j,k}$	integer constant
n_{ij}	number of lines to be added
α	factor associated for loss of load caused by lack of transmission capacity
γ	vector of virtual generation capacity
α_i	value of loss load
γ_{ik}	susceptances of line
c_{ge}	cost of generation
g_{ik}	generation capacity
T_k	duration of demand condition
ν	the total cost of expansion
w	cost of operation
C_{kl}	cost of adding a new line
n_{kl}	number of lines in the available right of way
α_1	cost of load shedding
γ_{Pk}	susceptances of the line
IC	investment cost
OC	operating cost
MC	maintenance cost
FC	failure cost
DC	disposal cost
NYE	number of years to be studied
i	annual discount rate in percent
CI	total per mile capital investment
F_L	line fixed charge rate in percent
ADC_n	per mile demand charge for line losses for year n
AEC_n	per mile energy charge for line losses for year n
C_{kW}	installed generation cost
ESC_n	escalation cost factor for year n
F_g	generation fixed charge rate in percent
RES	required generation reserve in percent
I_L	demand phase current in amperes per circuit
R	single conductor resistance in ohms per mile
N_C	number of conductors per phase
N_{ckt}	number of circuits
N_p	number of phases
C_{MWh}	cost of generating energy
L_f	loss factor for determining energy losses in percent
E_f	escalation rate in percent
AC	alternating current
ASCE	American society for civil engineers
ASTM	American society for testing and materials
ABC	artificial bee colony
BS	British standards
BIS	Bureau of Indian standards
COA	chaos optimal algorithm
CMVMO	collaborative mean variance mapping optimization
CORGA	combined real genetic algorithm and goal attainment
DEA	differential evolutionary algorithm
DC	direct current
EIA	environmental impact assessment
CENELAC	European committee for electrotechnical standardization
EA	evolutionary algorithms
EP	evolutionary programming
EHV	extra high voltage
EHVAC	extra high voltage alternating current
FACTS	flexible alternating current transmission system
GA	genetic algorithms
GRASP	greedy randomized adaptive search procedure
HPO	high phase order
HSIL	high surge impedance loading
HTLS	high temperature low sag
HVDC	high voltage direct current
HV	high voltage
IEEE	institute of electrical and electronics engineers
IEC	international electrotechnical commission
LCC	life cycle cost
MVMO	mean variance mapping optimization
MOX	mosquito behavior based
MOGA	multiobjective genetic algorithm
O&M	operation and maintenance
PSO	particle swarm optimization
PSA	parallel simulated annealing
PWRR	present worth of revenue required
R&D	research and development
ROI	return on investment
RoW	right of way
SFLA	shuffled frog leaping algorithm
SA	simulated annealing

STATCOM	static synchronous compensator	T&D	transmission and distribution
SSSC	static synchronous series compensator	UHV	ultra-high voltage
SAI	standards australia international	UHVAC	ultra-high voltage alternating current
SMB	standard board management	UPFC	unified power flow controller
TS	tabu search		

Transmission lines act as a connecting link between the generating stations and load centers and also between different transmission systems. Fig. 2 shows the general structure of the power system. Transmission systems are generally overhead systems as installation and maintenance cost is more in underground systems and also, control of voltage in long cables is difficult [15]. Underground transmission lines can be preferred in areas of heavy urbanization and other areas where overhead lines are prohibited in view of esthetics and public safety. Accelerated aging and consecutive damage is observed in underground lines due to long term over loading conditions. The time taken to repair the faults and the ability to upgrade overhead lines to higher voltage levels favor overhead transmission [16]. Overhead power transmission lines form the least cost method of transmitting electrical power as in most cases; the medium of insulation is air [17].

2.2. Planning

Transmission planning is aimed at installing new lines or expansions to meet the power demand at minimum cost with sufficient level of quality and reliability. Transmission line planning should start long before the construction activities are to be started. The time frame for planning can be divided into long, medium and short terms. Long term planning is done to identify technical requirements for new line installations and developing new technologies from a supply region perspective. Medium term planning concentrates on expansion programs and takes an interconnected system into consideration. Short term planning is done to analyze operating constraints and solutions for maintaining the continuity of quality power supply to the consumers [18]. The various technical, economic and environmental issues considered in transmission planning methodology are illustrated in Fig. 3.

2.3. Choice of line and voltage level

The choice for a particular type of line or voltage level depends on the amount of power to be transmitted over the line. Power transmission is usually done through AC systems at high voltage to minimize the transmission losses. The power transfer capability of the line increases and the transmission losses are minimized as the transmission voltage level is increased. This is one of the obvious reasons which are in favor of the utilities aiming for higher transmission voltages [19]. While there are several advantages of preferring high voltage for transmission such as reduced line losses, increased transmission efficiency and better voltage regulation, there are also some parameters which limit higher voltage level. These are increase in insulation required between the conductors and the earthed tower, increase in clearance required between conductors and ground resulting in increased height of towers and increase in distance required between the conductors resulting in requirement of longer cross-arms, all of these contribute in escalating the construction cost of the line. Every transmission line possesses a superior limit fixed for the voltage level to be employed, beyond which it is not economical [20].

AC transmission offers flexibility to step up and step down voltages using transformers wherever necessary. High voltage direct current (HVDC) systems are found to be advantageous in long distance transmission and for connecting two different AC systems [21,22]. Table 2 shows the voltage levels adopted for transmission of power in various countries across the world which are broadly classified as high voltage (HV), extra high voltage (EHV), ultra high voltage (UHV) and HVDC lines [23–24]. While

Table 2
Transmission voltage levels in various countries [22–25].

Country	HV (kV)	EHV (kV)	UHV (kV)	HVDC (kV)
Brazil	138, 230	345, 440, 500, 750	1000, 1500	1000
Canada	115, 230	345, 500, 735	1200, 1500	1200
China	220	500	1000	800
India	132, 220	400, 765	1200	800
Japan	110, 132, 154, 187, 220, 275	500	1000	650
Russia	110, 154, 220	330, 400, 750	1200	750
UK	110, 132, 275	400	–	500
USA	115, 138, 230	345, 500, 765	1200	800

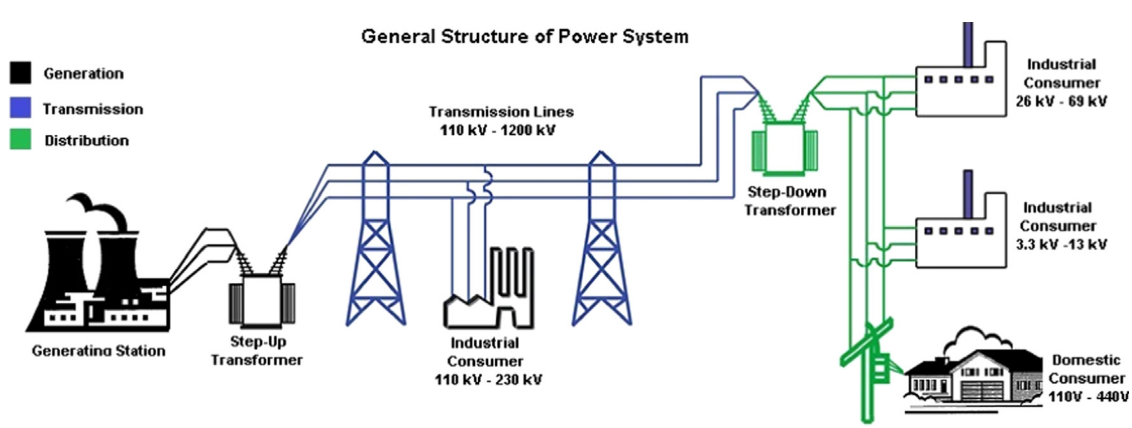

Fig. 2. General structure of power system.

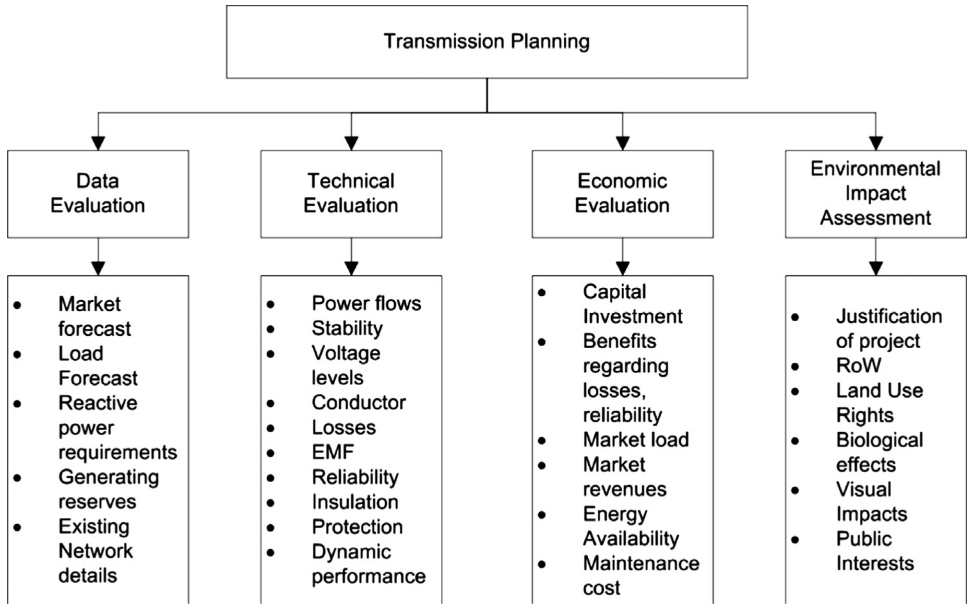

Fig. 3. Transmission planning methodology.

most of the UHV line voltages mentioned in Table 2 is in an experimental or testing stage, the last column indicates the highest operating voltage level of HVDC lines in various countries. Also, it is observed that UHV lines which are successfully commissioned and energized are being operated at a lower voltage level. The obvious reasons for this phenomenon are that, these lines are designed keeping in view future system capacity augmentation requirements, for interconnecting weakly coupled regions, to act as reinforcements for the areas with unpredictable and fast rate of generation and/or load growth apart from evacuating power generated from remotely located generating sources [25].

2.4. Construction of transmission lines

The construction of a transmission line is a complex laborious task requiring a coordinated execution plan at many individual sites simultaneously. The methodology for construction of the line is not unique throughout and changes from site to site depending on the terrain. Effective planning and organization management is necessary to achieve quality, construction to schedule and maximum economic benefits with minimum environmental damage. Fig. 4 shows the flowchart for the steps involved in construction of the transmission line. An overview of various stages involved in the construction of transmission lines was discussed by Adam et al. [15] and the comprehensive construction process is available in the literature [14,26].

The construction of transmission lines involves huge capital investments which are dependent on several technical, geographical, regulatory and other factors. Additionally, the degree of reliability and security plays significant role in enhancing the total cost. Certain factors like right of way (RoW) and land cost which are highly volatile and dependent on the market conditions, rise in labor cost, increase in raw material costs and economic parameters introduce a significant level of uncertainty in estimating the capital investment required for construction of transmission lines [27]. However, rated line voltage, cross section of the conductor and number of sub-conductors can be considered as the major parameters for estimating the line cost [28,29].

The time frame for construction of transmission lines is usually long due to many regulatory issues. Environmental impact assessment (EIA) studies have to be carried out involving major

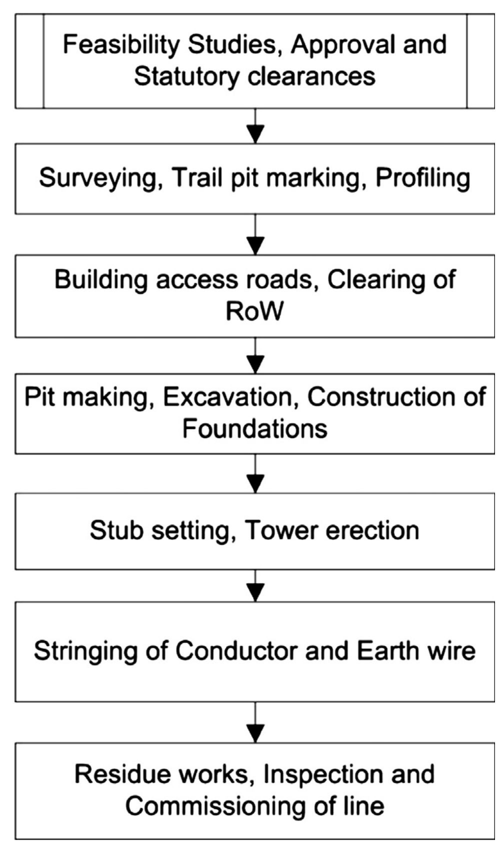

Fig. 4. Flow chart for transmission line construction.

stakeholders for project justification and to address various other factors. Permits and licenses are required from regulatory bodies for execution of transmission line construction works. The control posed by regulatory bodies varies from country to country depending on the local geographical and environmental constraints, but most of them address common features for obtaining the approvals and licenses [30]. In this regard, various guidelines were developed internationally by statutory authorities for

construction of transmission lines. However, many countries develop their own guidelines, mostly based on the international guidelines, taking into account the local climatic and geographic conditions. Table 3 gives information regarding the guidelines available in various countries for constructing transmission lines.

3. Current trends, challenges and recommendations

Global energy requirements tend to increase continuously posing a great demand for electricity. In order to meet the ever rising demand, large scale addition of new generation capacities is taking place which also necessitates augmentation of large transmission facilities between generation and bulk consumption points.

3.1. Current trends

There is a continuing trend towards the use of increasingly higher voltages and induction of new technologies for transmission of power. The evolution of voltage level began in 1891 with the commissioning of the first 15 kV three phase transmission lines in Germany to the 1200 kV line built in former Soviet Union in 1985 [14]. At present this is the highest operating transmission voltage in the world [32]. Fig. 5 illustrates the trend in voltage level growth in transmission systems. Efforts were made in the end of the 19th century to bring DC transmission into practice. DC lines require only 70% of the total investment costs as required for AC lines of the same power transfer capacity and presents 25–30% less ohmic losses, but the biggest challenge remained in the form of converting AC into DC and vice-versa economically and reliably [33]. DC lines are best suited for long distance bulk power transmission which offsets the capital cost investment of converter stations [34,35].

The distribution of generating resources is not uniformly spread across a nation and hence, construction of long distance transmission lines is inevitable. Transmission utilities across the world are now incorporating EHV and UHV AC lines, HVDC lines and flexible alternating current transmission systems (FACTS) technology into their transmission infrastructure to efficiently operate the transmission system [36–38]. The situation leading to this scenario results from the following:

a) Ever increasing power demands with fast economic growth;
b) Need for improved security, safety and reliability;

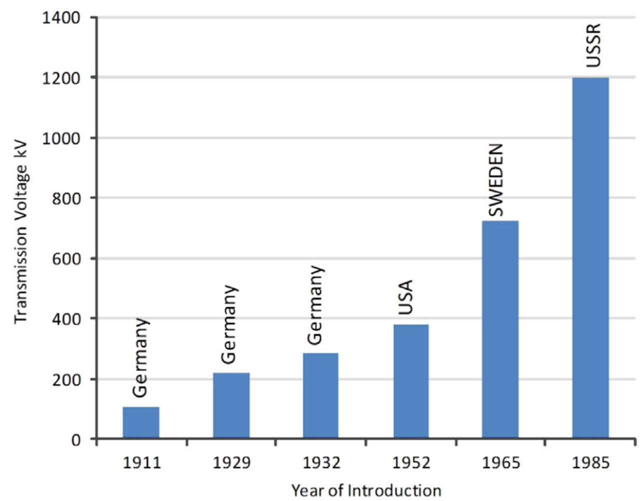

Fig. 5. Growth of transmission voltage level [14]

Table 3
Major standard guidelines adopted for construction of transmission lines in various countries [31].

Country	Agency	Guideline code			
		Conductors	Tower	Insulators	Hardware
America	American Society of Civil Engineers (ASCE)/American Society for Testing and Materials (ASTM)	ASTM B232, ASTM B779, ASTM B500	ASCE Standard 10-97, ASCE Manual 74 ASCE/SEI 48	ASTM A394, ASTM A363	
Australia	Standards Australia International, Ltd. (SAI)	AS1746, AS1531, AS3607, AS1222.1, AS1222.2, AS2841	AS1170, AS1289, AS2159, AS3995, AS4100	AS4398, AS2947, AS3608, AS3609	AS1154, AS4396
China	Department of Electric Power	DL/T5092, GBJ233			
England	British Standards (BS)	BS215	BS 8100, BS EN 1993 BS EN 1996, NA to BS EN 1998	BS3288, BS3297	BS2692, BS3170,
Europe	European Committee for Electrotechnical Standardization (CENELAC)	EN 1990–1994 and EN1997–1999			
IEC	Standard Management Board (SMB)	IEC 61394, IEC62420 IEC62219, IEC60889, IEC61089, IEC61395, IEC60104	IEC60826, IEC60652, IEC61773, IEC61774	IEC60305, IEC61325, IEC61109, IEC61952, IEC61467, IEC60433, IEC60383, IEC61211	IEC60099, IEC61284, IEC61854, IEC62271
IEEE	IEEE Standards Association	IEEE GUIDE 524 IEEE STD 738	IEEE STD 1441, IEEE GUIDE 691, IEEE GUIDE 977	ANSI C135	IEEE STD C135
India	Bureau of Indian Standards (BIS)	IS398, IS1778, IS2121	IS802	IS11182	IS5613, IS9511, IS9708, IS10162
New Zealand	Standards New Zealand	AS/NZS 7000:2010	BIP3024:2006	AS/NZS 4435.2:1999	BS3288

c) Optimal utilization of unevenly distributed generating reserves;
d) Development of national power grid;
e) Withstand issues posed by open access and energy market fluctuations;
f) Extract high concentrations of power from renewable energy rich areas;
g) Unconstrained economic dispatch;
h) Reduced environmental damage;
i) Flexibility of the transmission system to deal with future development and energy needs.

Apart from meeting the above mentioned necessities posed by energy demand, there are several other benefits to the transmission utilities employing high voltage lines. The benefits are in the form of monetary gain and effective operation and management of the grid [39–41]. The aim of the utilities and the advantages in preferring higher voltages for transmission are

a) increased transmission distance;
b) improved transmission capacity;
c) reduced line losses;
d) reduced project cost;
e) reduced land requirements;
f) promote power trading;
g) spacing between phases of high voltage lines minimizes the probability of phase to phase or three phase faults;
h) high voltage lines require fewer structures resulting in reduced visual impacts;
i) access to remote energy resources.

In recent years, transmission industry worldwide has seen a significant increase in the number of HVDC lines and FACTS controllers for control of power flow. AC systems are not directly controllable as the system impedance dictates the power flow. Generator scheduling and load control are the conventional means of adjusting power flow. However, for effective utilization of the transmission resources, a higher degree of control over power flow is essential. Conventional power flow control devices like series devices, shunt devices, voltage regulating transformers and phase shifters are not flexible as they employ mechanical switches which are slow in operation and also subjected to wear and tear [42,43]. In this situation, HVDC offers flexible power flow control. Power flow through a HVDC line can be controlled precisely and quickly by the use of converters capable of changing AC power to DC and vice-versa, along with modification to AC voltages at one or more converters, if necessary. FACTS based static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), and unified power flow controller (UPFC) are excellent power flow control devices. HVDC and FACTS can strengthen the power systems and also, improve their performance in increased dispersed generation scenarios [44,45].

3.2. Major challenges for development of transmission lines

Even though rapid developments are witnessed in the global transmission industry catering to the ever rising energy needs, there exist a number of challenges in several areas of transmission lines. Complexity in transmission interconnections, environmental and public safety, institutional/government policies and restrictions from regulatory bodies are some of the predominant challenges faced by transmission industry in developing new transmission corridors for meeting the energy requirements [46].

3.2.1. Technical issues

The growth of transmission lines, especially in the EHV and UHV range, is generally faced with many technical challenges. One of the foremost and persistent challenges concerning the transmission utilities regarding the development of transmission lines is the minimization of RoW. With the increase in the size of the synchronous interconnected transmission systems, problems due to load flows and inter-area power oscillations reduce the technical and economical advantages. The power transfer along a specified path in the system cannot be controlled by the system operator. Also, variations in power demand necessitate the need to regulate power flow on the transmission lines by flexible line loading for grid security and optimization [47]. The EHV and UHV lines, due to their high level of reactive power generation, are generally sub-optimally utilized which is a clear indication of under-utilization of the transmission investment. In this regard, there is a need for development of accurate computer models for exactly determining the conditions on the line enabling full use of transmission capacity. With the widespread use of renewable energy sources, integration of renewable energy generation to the grid, especially through weak AC links and when there is no sufficient reserve capacity available in the neighboring networks is a big challenge. A similar kind of problem is encountered in planning and stable operation of the transmission systems when dispersed generation is connected to the distribution system. The ever rising concern for environment poses the burden of reducing the biological effects due to electromagnetic fields and environmental impacts due to development of transmission lines [48].

3.2.2. Operational issues

Apart from the technical challenges, the construction of new transmission lines and uprating and upgrading of existing transmission lines are encountering many operational challenges. Some of the major issues include overloading of transmission line due to open access and free flow policies, loading of lines up to thermal limits due to deregulation, privatization and increasing congestion due to power trading with fast varying load patterns [49]. There is immense need for adopting reliability based online condition monitoring, repair and preventive maintenance for achieving zero forced outages and development of advanced tools for dealing with ever increasing data being measured and collected on the system [50,51]. Lack of timely information and inability to accommodate residual uncertainties for dealing with operational uncertainties increase the risk of outages.

3.2.3. Government/legal/policy issues

The role of governments, legal policies and regulatory bodies are vital in determining the growth of the transmission industry. Most of the issues dealing with these entities, from acquiring the license to redressal mechanisms are highly time consuming, delaying the construction of new transmission lines and in providing solutions for the difficulties encountered by stakeholders in the transmission industry. Acquisition of land, high capital investments in construction of new EHVAC, UHVAC and HVDC lines, sub-optimal planning leading to under-utilization of resources and insufficient focus on upgradation of existing transmission lines are the major administrative issues [52]. New RoW for transmission lines are environmentally interfering, complicated to route and subject to a very slow approval process as regulatory authorities are more and more disinclined to approve projects that do not address local needs posed by government policies. There is a much felt need for broader coordination of grid management in power system planning, development and operation, resulting in reduction in fixed and operating costs, lower risks and encourage better utilization of natural resources. Lack of

public policy addressing allocation of costs and benefits, redressal methods for unanticipated events, targeted planning for short, medium and long term energy transfers and incentives that support the required level of transmission investments are the major drawbacks in the policy matters hampering the construction of transmission lines. Inability to generate participation from established global players and participation from inexperienced players make the concept to commissioning time significantly high. Also, the uncertainties posed by electricity deregulation increase the gap between new technology developed and its actual employment for operational use [53].

3.3. Possible solutions for mitigation of challenges

The growth of transmission lines is inevitable even though their development is faced with a number of challenges. The ever rising global energy demand constantly emphasizes on constructing and augmenting transmission infrastructure using superior technology, improved operational practices and considering reforms in the policy/legal matters. The present section focuses on the possible solutions and recommendations for mitigation of the challenges.

3.3.1. Technical solutions

Majority of the technical issues need optimal planning strategies and measures, induction of new technologies and innovative designs. RoW concerns can be addressed through the development of high power intensity transmission corridors by increasing the transmission voltage. The usage of multi-circuit/bundle conductor lines on HV and EHV lines increases the power transfer per unit RoW available. Power transfer can be done using compact transmission towers employing delta configuration and narrow base towers which require less area when compared to normal towers. Also, upgradation of transmission lines to next higher voltage levels is to be considered for increasing power transfer capability of the existing transmission corridor with minor increase in RoW [54]. The loadability limits and conductor current ratings can be increased by employing high surge impedance loading (HSIL) lines and high temperature low sag (HTLS) conductors respectively. In some cases, reconductoring of existing lines proves to be an economic choice considering the useful life of the system. The use of composite materials like glass fiber can be used for replacing steel core in conductors for enhancing current carrying capability without increasing weight. Advanced conductor technologies such as cryogenic technology can be considered as a future option for development and operation of transmission lines with cryogenic conductors. Innovative technologies such as "Green towers" which involve designing towers with the least amount of steel and other metals aiding in lesser carbon emissions and resulting in lower carbon footprint can address environmental concerns. Development of hybrid transmissions consisting of DC and AC interconnections increases the operational flexibility while meeting the energy needs optimally [55].

3.3.2. Solutions to O&M issues

The operation and maintenance of transmission lines should focus on delivering power reliably and safely while maintaining the availability and security of the line. The areas signifying scope for improvement in operational activities of line include condition based monitoring to improve reliability, availability, life extension and operational efficiency. Preventive maintenance strategies are helpful in avoiding forced outages to some extent [56]. New technologies can enhance the power handling capacity, provide better dynamic reactive power support and minimize the construction of new transmission lines by reinforcing them into the existing grid. However, assessment of new technologies using comprehensive life-cycle analysis is recommended for evaluating their technical and economic viability [57]. Effective grid management is essential for managing transmission assets, operating methods and recognizing and evaluating alternatives for meeting transmission needs. The development of probabilistic, cost and risk management models helps in dealing with uncertainties in resource allocation, quantifying and analyzing contingencies impact on the system and optimum utilization of the system with required level of reliability respectively, while providing system operators with better information regarding system operational limits [58].

3.3.3. Government/legal/policy solutions

In the fast growing transmission industry where more and more capital investments are necessary, government provisions and regulatory policies should attract private investment in the transmission sector. Reforms in the transmission sector should be initiated by the institutional bodies for addressing the present issues, private and public sector transmission utilities are encountering. In this regard, incentives can be provided for public and private investors with policies for faster land acquisitions and environmental clearances. Incentives may also be provided for early commissioning and faster execution of transmission lines [59]. Policies should encourage investment in transmission R&D especially for development of cost efficient technologies which will enhance power transfer capacities in existing RoW. Institutional bodies must develop performance metrics to determine minimum planning and operational standards for transmission grid and apply stringent selection processes for filtering inexperienced participants [60]. Governments should take the lead responsibility in educating consumers to manage their distributed energy resources for reducing the dependence on conventional energy and encourage renewable energy growth, while providing redressal mechanism for unforeseen events. The policies should aim in providing system information needs to all market participants for making superior knowledgeable decisions regarding transmission system investments and also provide simplified exit norms which aid in asset churning [61].

4. Design and planning

The design of transmission line entirely depends on selection of appropriate data and parameters. The design of these lines is a very complex aspect as several design parameters have to be selected. The design parameters have complex interactions among themselves and in terms of their effect on overall system cost. A change in conductor design parameter such as diameter and configuration affects the tower loadings and foundation designs which further influences the construction process and total system cost. A continuous research for design and planning of transmission lines is essential in order to meet the energy demand with minimum environmental impact and maximum safety, adapt to the rules of statutory bodies and to achieve economy in materials utilization. The present section aims at reviewing the publications on basic and computer aided design aspects, policy issues, advantages of optimum designs, unconventional design methodologies, comparative studies among design methods and ongoing global trends in design of transmission lines.

Adam et al. [15] discussed in detail about the features of design and construction of overhead lines above 132 kV envisaging the importance of load and strength assessment concept by statistical means to define reliability of the system. Important aspects in transmission line construction via loadings, conductor properties, insulators and insulation levels, tower structures, foundations for

towers, methods of construction depending on terrain and problems encountered during the design and construction stages are discussed in detail. Orawski [17] presented the design considerations with respect to various design parameters and construction aspects of overhead transmission line engineering. The need for calculating the present day worth of different solutions, which take into account the cost of the losses and the capital invested, is emphasized. The conclusions from the study indicate that according to CIGRE WG22 report, future changes in design would be based on static and dynamic rating of conductors, use of meteorological data for system operation, effective use of RoW, government policies, assessment of condition and expectancy of aged lines, component diagnostics and diagnostic techniques.

Robert [62,63] discussed about the transmission line design and construction concepts, empirically developed practices for design and construction of 500 kV lines in Los Angeles Department of Water and Power, USA. The study highlights the necessity to reduce field effects of transmission lines on living beings and the methods to reduce the same were suggested. Ash et al. [64] proposed a conductor selection methodology basing on service experience and environmental considerations which is a task of optimization and balancing of conflicting requirements. The reasons for the predominance of aluminum-based conductors and all the associated factors were discussed. Wood et al. [65] designed transmission lines based on the ultimate load concept considering statistically deduced data which include strength coordination and various loads acting on the tower. A novel method integrating the practicality of the ruling span concept with the accuracy of the three dimensional vector method for analysis of inclined spans, most efficient for design of overhead lines in mountainous terrain was presented by Keselman and Motlis [66]. Bradbury et al. [67] presented a method for calculation of sag and span based on the analysis of the change of state equation for mountainous terrain where traditional techniques to measure sag may be impractical and results in deviated results. Armitt et al. [68] discussed a methodology for calculation of wind forces on components of overhead lines considering the properties of the atmospheric wind incident on the line based on a statistical approach.

Douglass [69] developed a sophisticated line design program which incorporates structural analysis to estimate the economic value of changes in the conductor parameters and suggested potential areas for cost savings. Results indicated that the largest potential for cost savings appears to be in increased unloaded tension, reduced overall conductor diameter, reduced thermal elongation of aluminum strands and no significant cost savings were found for reduced thermal elongation of steel core, reduced creep elongation and increased elastic modulus. The effect of phase-to-phase compaction was economically significant for the double circuit lines but not for the single circuit lines. The effect of increase in conductivity was neither significant nor negligible. Cleobury [70] recommended the maintenance of a database management system for planning and operating purposes by utilities. The function of the transmission system, future trends, planning time horizon and planning criteria along with the importance of computer simulations for these studies were discussed.

Peyrot et al. [71] developed an integrated computerized model which provides three dimensional access to the entire line and its RoW. The model provides a complete illustration of the topography under the line, cables, insulators and structures in all the spans. The objective of the integrated and interactive environment for given topographic data in electronic form is to, enable the designer performing the total line engineering and acquire all the requisite documents for its construction. Picard et al. [72] developed a knowledge based system consisting of a record of tower configurations and allied parameters to assess transmission line costs for various AC voltage levels subjected to environmental constraints. Jung and Biletskiy [73] developed prototype automation software for evaluating and comparing economical efficiency of AC and HVDC transmissions. The software determines appropriate transmission line types during planning and construction stages among the possible alternatives by performing economic analysis.

Luis et al. [74] demonstrated that coordination and exchange of functions, information and services across the transmission distribution interface results in maximum efficiency in planning and operating the transmission system. The authors presented review about the incorporation of certain characteristics in future transmission planning aspects, critical issues the transmission grids have to concern, security and reliability criteria's, deregulation, efficiency considerations and research on transmission planning. The author (s) stressed the need for development of dynamic and pseudo-dynamic models for transmission planning in contrast to the static models being used by the transmission planning researchers. Shalini and Paul [75] developed a policy level framework to access difficulties in siting, based on several datasets and statistical analysis. A two step policy level framework was presented that first develops an empirical measure of siting difficulty and then quantitatively assesses its major causes. The study provided breaking down the causes of siting problems into manageable pieces for evaluation and planning, while simultaneously maintaining a large-scale view of the problem. It was concluded that public conflict is the most imperative aspect in siting problems followed by consultants' perceptions.

Marija et al. [76] presented a survey article defining and evaluating transmission capacity, providing economic incentives and means of increasing it in a changing electric power industry. Ralph [77] discussed the benefits of managing congestion through organization of systematic transmission rights and interconnector usage. Methods for dealing with complex problems arising when several interconnectors are used to provide meshed links between several control areas were proposed. Wullur and Pharmatrisanti [78] presented a method for transmission line condition assessment based on failure mode effects and criticality analysis. Sabharwal [79] proposed a procedure incorporating the transmission and distribution costs in the electricity supply cost to the rural load centers which includes the capacity and operating costs of generation, transmission and distribution.

Fenton and Nancy [80] presented a methodology for optimum design of the transmission lines considering uncertainties in both environmental loads and structural resistance to achieve acceptable reliability at reasonable cost. Brian [81] investigated on structural optimization of transmission line conductors and found that selection of necessary amount of steel reinforcing or alloying was found to be the basis for good structural optimization of the line. The author suggested considering conductor steel or alloy as a part of structural support system along with steel of towers, both of which serve the purpose of supporting aluminum of conductors. Vajeth and Dama [82] and Dama et al. [83] formulated a procedure for optimizing the configurations of towers and conductors during the selection process considering overall view of the system. The optimization algorithm incorporates considerations regarding planning, load forecast, power quality constraints, voltage collapse, corona, audible noise, transposition, line performance and life cycle cost of maintenance for available alternatives. The effectiveness of this algorithm is tested by implementing it for an actual case study and is found to be useful in the selection of conductor and tower configurations for new overhead transmission lines. Design optimization studies of transmission line with respect to structure and materials as variable parameters using StaadPro and ANSYS softwares was performed by Raghavendra [84].

Baldick and Neill [85] estimated the costs of increasing transmission system capability through FACTS technologies which increase transmission capacity without expanding the existing

footprint. Stewart et al. [86–90] presented a comparative study on high phase order (HPO) to UHV systems. Results indicated that for the same power capacity, terminal equipment costs higher and transmission line present worth is less for HPO than UHV. For lines longer than a few miles, savings in the line offset the terminal equipment costs, indicating that HPO is an alternative to UHV, at similar or possibly less cost. In addition, HPO lines will be smaller than UHV, and will probably require less RoW. Hanson et al. [91] presented the relative advantages, disadvantages and cost comparisons for upgrading the existing transmission lines. The case study of four transmission line projects upgraded with increase in number of conductors, conductor size, voltage level and modifications in tower structure showed that the lines were upgraded successfully with satisfactory performance at 50–60% of the cost of the new transmission lines. Piernot and Leahy [92] conducted a case study on three existing lines which were upgraded by increasing operating temperatures and capacity and the results were analyzed in the form of increase in additional power handling capacity and return on investment (RoI) on the total amount spent for upgrading the lines. Mooney [93] developed a technique to economically justify transmission line transposition. The technique is based on cost comparisons of the transposition towers and the line losses for a transposed and untransposed line over the useful life of the line. Procedures for computing three phase line losses under unbalanced conditions and the net present value of the line losses were presented.

Berjozkina et al. [94] performed a comparative analysis for evaluating the technical and economic efficiencies of replacing the existing conductors with HTLS conductor. Evaluation of technical efficiency is performed considering wind pressure, ice thickness, minimum and maximum air temperature and average operating temperature while evaluation of economical efficiency was performed considering costs of conductors, supports, foundations, strings and installation costs. A comparative analysis and design of 400 kV three legged and four legged transmission towers is performed according to IS: 802 (1995) by Ghugal and Salunkhe [95] and a saving of steel weight up to 21.2% was achieved in the three legged case. A detailed research on 220 kV narrow based towers in China was carried out to use in areas where available right of way width is insufficient by Jun et al. [96]. Jiang and Deng [97] discussed the different methods of wind loading prediction for transmission line between Chinese new code and other existing international standards. Sakhavati et al. [98] and Kishore and Singal [99] presented a methodology for design of 765 kV single circuit transmission line and compared the advantages with other low voltage lines. Larruskian et al. [100] discussed about the advantages and possible means of incorporating HVDC systems over AC systems in present day power systems.

The practices and trends in growth of EHV and UHV transmission globally have been reported in the literature. The earlier researches essentially aimed at environmental considerations for establishing these lines, selection of technical and economical parameters and testing of lines [101–104]. Issues with introduction of transmission lines above 700 kV were discussed by Kim et al. [105] and Lings [106]. These studies provided information regarding system planning, electrical design, mechanical and tower design, and the operation and maintenance experience of lines above 700 kV. Nayak et al. [107] presented a mathematical model for increasing the surge impedance loading level of a line towards its thermal limit for enhancing the transmission line capacity. Sensitivity of surge impedance loading on various configurations of sub-conductors in a bundle, bundle spacing, tower structure, spacing of phase conductors, etc. was analyzed. The studies conducted on the model concluded that HSIL lines having expanded bundle geometry optimizes the electric field at the surface of all sub-conductors reducing the inductance. HSIL lines offer other advantages like enhanced power transfer capacity, improved stability limit, better voltage regulation, reduced transmission losses, reduced environmental impact and optimization of transmission cost.

Grant and Clayton [108] developed a methodology to investigate the sensitivity of the PWRR to a number of design variables of the transmission line. The procedures contain comprehensive cost models including strongly interactive line design variables that are essential if comparisons are to be valid for major design modifications. The model is used for optimizing the cost of tower structures and foundations which is given by

$$\text{Cost} = \text{Unit cost} \times \text{weight} \tag{1}$$

$$\text{Weight} = C_0 + C_1 H + C_2\ P + C_3\ \text{Vertical} + C_4\, L + C_5\, T \tag{2}$$

where $C_n(n=1,2,3\ldots,n)$ are the geometry and loading gradients obtained from regression analysis, H is the height of the tower and P, V, L, and T are the phase, vertical, longitudinal and traverse spacing respectively. The authors concluded that, primary optimization, i.e. the choice of the major line parameters such as conductor system, structure type and span, typically influence items comprising 70–80% of the line PWRR and secondary optimization, such as tower geometry and detailed design, has negligible economic effect and can be performed without disturbing the primary optimization choices. Kennon and Douglass [109] developed a range of transmission line optimization techniques for making a selection between standard and optimized line designs. It has been found that even simple methods of optimization can help the designer to minimize the costs. Three types of optimization methods were described for transmission lines viz. conductor optimization, conductor and structure optimization and conductor, structure and design limit optimization. These methods are capable of indicating potential cost saving areas in EHV transmission lines through line optimization.

Peyrot et al. [110] studied the roles of standardization and optimization in selecting transmission line design parameters. A primary optimization consisting of conductor and structure family and a secondary optimization for structure spotting was investigated. Optimization using structure spotting program was carried out in both directions as the terrain is not symmetrical, the total terrain length is not necessarily an integral number of spotting intervals and the solution costs are not always identical in the forward and reverse directions. The differences are small and become negligible with lesser interval spotting range and the probability of obtaining optimum solution is when both the forward and reversed solutions converged at the same point. It was demonstrated that the savings realized by using an optimum spotting program on a medium line length were more than the cost of acquiring the technology and training for its use. Research on uprating of existing lines, voltage selection and insulation design requirements, were carried out on existing transmission lines [111–115].

5. Modeling and optimization

The theoretical and scientific studies for a project under consideration can be performed by modeling, which mimics most of the relevant features of the project [116]. Modeling is done to design, analyze and optimize a mathematical representation of the system for studying the effect of changes to system variables. The process of optimization of a transmission line involves simultaneous studies and analysis for design and selection of various components of the line to achieve overall cost optimum techno-economic design [117]. The design of overhead power line is therefore faced with selecting design parameters which have

complex interactions in terms of their effect on the cost of the system. The selection of these parameters is also bounded by external constraints. The cost associated with selection of the conductors is such that it increases as the size of the conductor increases, while transmission losses decrease. The lower limit on conductor size below which a conductor cannot be used is governed by radio interference to be tolerated. An increase in the number of conductors in a bundle decreases the energy loss while increasing the conductor cost. A larger conductor reduces the transmission loss but produces heavier loads on a supporting tower and thus requires a heavier and costlier tower. The span length between adjacent towers has a direct effect on the loads that the towers must support. The greater the span length, the greater the loads and thus an increase in tower weight is essential. However, an increase in span length reduces the total number of towers required for a given length of transmission line. In this regard, design optimization of overhead power lines considering various possible configurations involving all major parameters can be implemented to achieve an acceptable performance keeping the costs to a minimum [118].

Optimization techniques form a suitable tool for solving complex problems in the field of transmission lines through mathematical modeling. In tackling the problems related to transmission lines, many studies have been performed by earlier researchers. Most of these studies have delivered promising results in terms of reducing capital costs and increasing system reliability. Although mathematical models are the most sought after methods for modeling, some of the major drawbacks regarding these methods are no user interaction, intractable models, requirement of large number of decision variables and long computational times [119]. Researchers are continuously proposing and applying new methods. Researchers nowadays prefer heuristic and meta-heuristic techniques which can efficiently handle these drawbacks and many optimal transmission lines models have been developed. A critical review of different techniques employed in transmission lines development has been carried out in this study. For ease of reference and to facilitate understanding, these are categorized into three major headings based on problem formulation as mathematical techniques, heuristic and meta-heuristic techniques and other promising techniques.

5.1. Mathematical optimization models

Mathematical optimization models provide an optimum solution by solving a mathematical formulation of the problem. Due to the impossibility of considering all aspects of the transmission line optimization problem, the solution obtained is the optimum only under large simplifications. The transmission line problems in the recent days are seen as a matter of “decision making” and not solely “optimization” and hence a thorough verification of the solution obtained must be made by the decision maker before taking decisions [120]. The transmission line optimization problem is considered as a transmission planning problem in formulating the mathematical optimization models. These models aim at reducing the capital cost in planning new lines in existing or new networks, considering network operating conditions and reliability into account. The models consist of an objective function subjected to a set of constraints. Objective function is a measure of goodness of each solution obtained and the constraints try to model the problem close to reality by imposing criteria faced in real time planning of transmission lines [121].

Classical methods played a major role in the early days of research on transmission line optimization. The classical methods of optimization are useful in finding the optimum solution of continuous and differentiable functions. These methods are analytical and make use of the techniques of differential calculus in determining the optimum points. Several methods have been proposed by using classical optimization techniques like linear programming [122–127], nonlinear programming [128], dynamic programming [129–131] and mixed integer programming [132–144]. Garver [122] proposed a linear flow estimation technique which is used in network estimation for producing feasible transmission networks with minimum circuit miles. Any existing network plus a load and generation schedule can be given as input to the system. The advantages of the method are flexibility to study networks with multiple voltage levels, synthesis of future transmission networks with circuit additions and implementation of AC load flow. This model was implemented on a six bus system and the results were justified by AC load flow calculations for determining the transmission investment costs in generation transmission expansion studies. Kattenbach et al. [123] proposed a DC load flow approach to find the minimum cost capacity additions required to accommodate known changes in demands and generation. An expansion schedule involving linear and dynamic programming methods was produced. The required input data are the yearly load, generator nodes and magnitudes, the cost of losses and the cost of permissible line additions per mile. The program tests for reliability by solving the yearly load flows for overloads and accounts only for single outages.

Villasana et al. [124] proposed a new method for long range transmission planning by the combined use of linear power flow transmission and transportation models. The former is solved for the network by Kirchhoff's laws and the latter is solved for the overloads by using only the bus flow conservation law while minimizing a cost objective function. The objective function proposed for use with this method is given below

$$\min\ C = [C_D^t][\ |P_D|\ ] \tag{3}$$

where $[C_D^t]$ is the transposed vector of cost of overload flows and $[\ |P_D|]$ is the vector of undirected overload flows on path D. The model was implemented on a 6-bus system and the results indicated that the linear programming solution of the two models together identify capacity shortages in the network. The transportation model helps in selecting new lines and is completely unused when the network design is complete and contains no overloads. Mutale and Strbac [127] presented a linear programming approach for computing the maximum savings in operating costs that could be achieved from the installation of FACTS and to assess its competitiveness against network reinforcement. Youseff and Hackman [128] proposed a new model for optimal planning of long range transmission networks capable of dealing static and dynamic modes. The linear cost function is formulated so as to include fixed and variable costs apart from cost of power losses, and is optimized according to the demand criterion and overloading conditions. Results indicated that the inclusion of security constraints on bus voltage magnitudes and swing angles and AC load flow in the same model makes it more advantageous in optimal planning of power networks. Olbrycht [129,130] presented a dynamic programming model for tower spotting, along the transmission line route, which determines a set of consecutive cheapest solutions accounting for minimum construction costs. Seifu et al. [134] and Choi et al. [141] presented modeling of systems with reliability constraints which account for outage, contingency and unserved energy costs.

Sharifnia and Aashtiani [136] proposed a mixed integer method for solving the problem of minimum cost expansion of power transmission networks. The model considers investment costs of new lines and the operating costs associated with the system, embedding the DC load flow equations for the network in the constraints to avoid sub-optimal solutions giving the best line additions. The basic model used for implementation of the

optimization algorithm is given by

$$\text{Minimize } \sum_{i \in 1}^{N} C_i G_i + \sum_{j \in 1}^{A} K_j Z_j \tag{4}$$

where N is the set of all buses, A is the set of all lines, C_i is the per unit generation cost, G_i is the maximum generation capacity, K_j is the capital cost of new line and Z_j is the integer constant. Alseddiqui and Thomas [139] proposed a mixed integer nonlinear multi-objective and single objective optimization methodology for contemporary transmission expansion planning used to reduce total system operating cost and line construction/cost. The objectives and the constraints may be conflicting, non-conflicting and/or uncertain relationships. Contingency analysis was performed to analyze the system security. The method was implemented on IEEE 3 and 118 bus systems and local pareto optimal solutions were determined. Farrag and El-Metwally [140] presented a simulation model using mixed integer linear programming for planning of high voltage transmission networks. The model considers the capital investment cost and cost of transmission losses with DC load flow equations and line loading as constraints. The cost function to be minimized is given below

$$\min\ F = \sum_{i=1}^{M1} \sum_{j=1}^{NS(i)} (C_{ij} Z_{ij} + S_{ij} P_{ij}) + \sum_{i=1}^{M2} W_i PR_i \tag{5}$$

where F is the value of the actual system cost, $M1$ is the number of proposed lines, $NS(i)$ is the number of states of the proposed line, C_{ij} is the capital cost of the proposed line, Z_{ij} is zero one integer variable assigned to the proposed line, S_{ij} is the linearized cost coefficient, P_{ij} is the power flow, $M2$ is the number of existing lines, W_i is the linearized cost coefficient of transmission losses and PR_i is the power flow in existing lines. The model was implemented on the six bus system and the results indicated that the model can be used to obtain the least cost network satisfying line loading constraints for all static planning problems irrespective of system size. The advantage of this model is its ability to include linearized cost of transmission losses and actual simulation for reconductoring of existing lines.

Khodr [142] proposed a novel optimization methodology for the design of transmission line grounding systems, considering technical and economic parameters. The objective function to be minimized is comprised of a linear function describing the investment of variable components as the sum of the investment in counterpoises and rods. Real time implementation on a 230 kV transmission line, 85.4 km long, with 180 towers was carried out using two different simulation approaches for investigating the behavior of the line under lightning phenomenon without generality loss. The author concluded that the methodology selects a set of matching grounding electrode schemes which result in savings in the investment costs, enforcing the given forced outage rate value of the transmission line. Sawey and Zinn [143] proposed a mixed linear integer programming model for minimizing the net present value of the total system cost consisting of capital cost and system operating costs associated with construction of power plants and transmission lines along with system operating costs. Forecasted demands, limited capital resources and plant site limitations are considered as constraints. The general representation of the mathematical model developed is given by

$$TC_{sys} = \text{Minimize } ax + bz \tag{6}$$

Subjected to $Ax + Bz \le c$, $X = 0$ or 1 and $z \ge 0$

where TC_{sys} is the total cost of system, A and B are matrices and a, b, c, x, z are vectors of appropriate dimensions. The results of this model are a construction schedule which includes the capacity, location, operating schedules and time schedules for completion of the project.

Solution of large linear programming problems can be successfully obtained by Benders decomposition [145–151] and hierarchical decomposition [152]. In Benders decomposition, the network design problem is divided into master and slave subproblems. Modeling of investment variables and network expansion plan proposal is done by master sub-problem and implementing of the proposed plans and checking for network feasibility is taken care by slave sub-problem. The iteration between both subproblems is characterized by Benders cuts, which are evaluated from the slave's solution and added to the master sub-problem [145,146]. The power transmission network design problem is usually modeled as a mixed, nonlinear, non-convex formulation for use with this technique. Neglecting the combinatorial nature of the problem, handling with the non-convexities of feasible region have been the main drawback for using this formulation in practical studies [147]. Romero and Monticelli [152] presented a Benders hierarchical decomposition approach for dealing with the above non-convexities, where the power network constraints were represented by a chain of three models. The two first models relax all the non-convexities constraints, which results in the optimal solution and then, the non-convexities are introduced into the third model. Branch and bound algorithm offers solution to transmission line planning problems by combining decomposition and other techniques [153].

Khaki et al. [154] proposed an optimization method combining linear programming with dynamic thermal rating for cost/loss minimization. The method considers thermal ratings of conductors in the design of transmission lines, as designs based on static thermal ratings were underutilized apart from their inability to completely eliminate circuit failures. The required data was obtained from spatially resolved thermal models of transmission lines based on actual weather conditions. The objective function used for cost minimization is given by

$$Z(t) = \min \sum_{i=1}^{N} [CF_i \times \Delta t + CV_i \times PG_i(t) \tag{7}$$

where Z is the total generation cost/transmission losses, N is the number of buses, CF_i is the fixed costs of power generation, CV_i is the variable cost of power generation, $PG_i(t)$ is the power generation at bus i and Δt is the simulation time step length. Results concluded that the model accounts for power loss accurately since actual distribution of temperature dependent conductor resistance was considered along the line. Since some of the practical problems involve objective functions that are not continuous and/or differentiable, the classical optimization techniques have limited scope in practical applications. The intrinsic limitation of the mathematical optimization procedures poses problems which are non-convex and nonlinear in nature. Long computational times, no user interaction, intractable models and requirement of large number of decision variables are considered as major setbacks of mathematical models. The basic objective(s), the merits as well as the demerits of these optimization techniques are presented in Table 4.

5.2. Heuristic and meta-heuristic optimization models

Heuristic models provide an excellent alternative to mathematical models. The term heuristic originates from the Greek word 'heuriskein' which means to discover or to find. These models use a step-by-step generating, evaluating and selecting options for obtaining a solution. Heuristic methods need lesser computational times as compared to exact methods and yield a good, but not necessarily optimum solution. Based on the nature of the heuristic method they are classified as decomposition, inductive, reduction, constructive and local search methods [155]. Among these local search methods are popularly used by the researchers. Local

Table 4
Comparison of various techniques for transmission line modeling and optimization.

S No	Problem type	Technique/approach	Objective function	Merits	Demerits	References
(A) Classical techniques						
1	Linear optimization problem	Linear flow estimation technique	Minimization of loss function	– Flexibility to – analyze existing – and new networks – Highly reliable	Only one circuit can be added at a time to reduce overloaded paths	[122,127]
2	Linear power flow problem	Linear and dynamic programming technique, look ahead factor method	Minimization of cost for capacity addition	– Accounts for reliability – Considers investment and operating costs	– Generation and demand forecasting is not on real time basis	[123,126]
3	Non-linear optimization problem	First order gradient search technique, applied regression analysis	Minimization of Cost	Considers all system parameters simultaneously	– Requires good guess for starting vector – Regression results are highly variable depending on input data	[118,128]
4	Discrete dynamic optimization problem	Dynamic programming and Probabilistic Search (Forward & Backward) Technique	Optimal construction of neighboring network	– Calculate a number of feasible strategies – Evaluates the performance of alternative strategies	– Solution obtained is at fixed time intervals	[131]
5	Mixed integer programming problem	Branch & bound algorithm, benders decomposition techniques	Minimization of Investment Cost	– Considers static and dynamic stages of planning – Determines all possible feasible integer solutions	– Inaccurate then the DC load flow model – Time consuming process	[132,133,138,144]
6	Non-linear mixed integer network flow problem	Implicit enumeration search procedure	Minimization of network expansion Cost	– considers economic and technical objectives – Low computational effort	– static model	[135]
7	Discrete time deterministic optimal control problem	Nonlinear branch & bound dynamic optimization procedure	Minimization of network expansion Cost	– Less computational burden – Ability to eliminate infeasible and non optimal solutions	– Accounts for single stage security and reliability outages	[137,140]
8	Mixed-integer nonlinear multi-objective optimization	Non-linear branch and bound method, weighted metrics method	Minimization of total system cost, investment/construction cost, and contingency analysis subject to network constraints.	Generates Pareto optimal solutions	Difficult and computationally intensive	[139]
9	Mixed linear disjunctive optimization	Benders decomposition	Minimization of Investment Cost	– Use of Gomory and Benders cuts for arriving at optimal solution	– complex investment sub-problems – high computational times	[148]
(B) Heuristic techniques						
10	Mixed integer linear optimization problem	Mixed integer programming and heuristic technique	Minimize present cost of capacity addition	– Ability to find optimum solution with and without outages	– Multiple contingencies are not considered	[134,143]
11	Linear power flow problem	Benders decomposition and heuristic search method	Minimization of cost of expansion plan	– less computational time – considers both static and dynamic planning	– More iterations – priority to each variable is to be set after each iteration	[149]
12	Long term transmission planning problem	Hierarchical decomposition method	Minimization of cost	– Deals with transportation, linear, nonlinear and hybrid models – less iterations	Two or more models are required to solve a single optimization problem	[152]
13	Linear power flow problem	Decomposition method, Monte Carlo simulation	Minimization of total system expansion cost	– Solved by decomposing the problem into minimum load curtailment problem and local marginal network problem – Inclusion of reliability constraints and control strategies	– Static model – Based on assumption that load and generation forecasting is done – High computational time	[157]
14	Sensitivity analysis of linear	Sparse technique, Ranking algorithm	Identify compatible performance indices for transmission system in terms	Identification of circuit overloads or violation of bus voltage limits.	– sensitivity index cannot be determined	[159]

Table 4 (*continued*)

S No	Problem type	Technique/approach	Objective function	Merits	Demerits	References
	transmission networks		of load shedding or load supplying capability		– w.r.t. pairs of buses which were not originally – connected. – Only a reduced number of circuits will have f lows – at their limits in the optimal solution of the LP problem	
15	DC load flow problem	Steepest-descent algorithm	Minimize the costs of installing transmission line capacity and of penalizing overloads	Reduce the size of alternative planning networks with considerable savings in cost	– Static planning – Line outages not considered – algorithm performance depends on step magnitude prediction	[162]
(C) Meta-heuristic techniques						
16	Dynamic transmission planning problem	Genetic algorithm using transmission sensitivity information	Minimize transmission investment	– Optimization is achieved by controlling transmission investment decision in deregulated environment – Ability to deal large search spaces	– Present difficulty in performing local search – Performance of GA detoriates after “good” range	[169,226]
17	Non-linear mixed integer convex optimization problem	Improved genetic algorithm using simulated annealing	Minimize transmission investment and loss cost	Use of decimal coding and improvement of result using fine tuning techniques	High computational time	[171]
18	Multi-objective optimization problem	Multi-objective genetic algorithm (MOGA)	Minimize circuit investment and maximize reliability efficiency	Allows to change the shape of the dominance region specifying maximal and minimal trade-offs between the different objectives so as to efficiently guide the MOGA towards Pareto-optimal solutions within the boundaries	– direction of power flow is not accounted – no benefit to transmission capacity of electrical network	[183,184]
19	Mixed integer non-linear programming problem	Parallel simulated annealing (PSA)	Minimization of network expansion cost	Better performance than sequential simulated annealing (SSA)	High computational burden	[185,186]
20	Mixed integer non-linear programming problem	Parallel tabu search	Minimize cost of circuit addition	– Ability to handle number of configurations – Better search performance than SA and GA	– Optimality highly depends on tabu list manipulation – possibility of converging at local optima due to intensification process	[187,193,194]
21	Mixed integer non-linear programming problem	Stochastic optimization method using evolutionary programming	Minimization of investment and operational cost	– Don not require coding of decision variables as GA – Less computational burden – Fine tuning of control parameters	– Computational burden and optimality highly depends on initial solution	[188]
22	Mixed integer non-linear programming problem	Differential evolutionary algorithm (DEA)	Minimize the transmission investment cost	– Accounts with and without the resizing of power generation – Includes right of way constraints	– high computational time – possibility of premature convergence	[189,190]
23	Mixed integer, non-linear, non-convex combinatorial problem	Local PSO	Minimize cost of circuit addition	Cost effective, robust parallel processing approach	– Convergence is slow and premature – Feasible and unfeasible search spaces are included	[195,197]

Table 4 (*continued*)

S No	Problem type	Technique/approach	Objective function	Merits	Demerits	References
24	Discrete non-linear optimization problem	Improved discrete PSO with mutation technique	Control expanded lines adequacy rate with investment cost inserted to problem constraints	– Solution is obtained by merging lines loading parameter expansion planning and investment cost into the fitness – Function constraints – Increased precession without premature convergence	– Solution depends on adequacy index on expansion cost rate – Convergence speed is less compared to DPSO	[198]
25	Integer multi-objective optimization problem	Integer multiobjective particle swarm optimization (IMOPSO) algorithm	Minimization of cost and Maximize reliability of network	Robust and highly capable of obtaining pareto optimal front solutions	Solution depends on inertia weight factor	[199]
(D) Other promising techniques						
26	Constrained Multi-objective optimization problem	Real GA with goal attainment method (CORGA) and fuzzy logic	Minimize cost of expansion and load curtailment	– Ability to converge under uncertain demand fluctuations – Does not require any coding and decoding stages – Faster and more accurate than binary GA	– Complexity in codification – Solution fitness depends on membership degree	[200]
27	Nonlinear discrete optimization problem	Chaos optimization algorithm (COA)	Minimize investment and attain best distribution of branch load factors	– Considers surplus capacity and load factors avoiding decongestion – Improves flexibility of dispatch	Convergence not guaranteed if unfeasible search spaces are present	[201]
28	Mixed integer optimization problem	Shuffled frog leaping algorithm (SFLA)	Minimize total cost	– Accounts for costs of congestion and contingencies – Converges faster than PSO and GA	– Only one contingency is considered at a time – RoW is restricted to reduce search space and save computational time	[203]
29	Mixed integer nonlinear optimization problem	Collaborative mean-variance mapping optimization (CMVMO)	Minimize cost of new circuit addition	– Fast convergence – Accounts for load deficit caused by lack of transmission capacity	– more iterations – moderate success rate for convergence	[208]
30	DC power flow model	Mosquitoes-behavior based (MOX) Evolutionary Algorithm	Minimize the transmission network investment cost	– Meets load growth and generation patterns maintaining the system reliability	Solution depend on large number of input parameter settings	[209]
31	Large-scale, mixed-integer, non-linear programming problem	Local controlled random search (simulated rebounding algorithm)	Minimize expansion cost	– Better performance than GA, PSO and SA – Considers multi-stage security constraints	Requirement of more number of initial parameters and their settings.	[211]
32	Static transmission expansion planning problem	Artificial bee colony (ABC) algorithm	Minimize to the investment cost	– Accounts with and without the resizing of power generation	Several number of tests are to be done to find control parameters for best solution	[212]
33	Transmission network expansion problem	Greedy randomized adaptive search procedure (GRASP)	Minimum Load curtailment	– Generic and simple – Solution is obtained in two phases i.e. construction and local search phase	– Time consuming – difficulties in local search method	[213]
34	Mixed integer non-linear optimization problem	Harmony search algorithm	Minimize total investment cost of the new transmission lines	– Accounts for real power flows and $N-1$ contingencies – Less mathematical requirements – Simple and effective	Multi-stage contingencies not considered	[214]

search starts with a feasible solution for the problem and progressively improves it. Each procedure step traverses from one solution to another one with a better value. The search is carried out with the guidance of empirical or logical rules and sensitivities used to generate and classify options during the search. Termination for a solution occurs when there is no other accessible solution that improves it.

Fischl [156] proposed the first heuristic procedure to minimize capital cost by producing the required susceptance changes in the DC power flow model. The concept of "adjoin network" and "nearest neighbor" was used to determine the closest values of susceptances. Levi et al. [157] proposed a mathematical optimization algorithm combined with heuristic decomposition to control the power flow by penalizing through guide members and assures that the model uses first, all the real circuit capacity. Lattore [158] proposed the heuristic method based on natural decomposition for transmission planning problem for operation and investment sub-problems. The optimization model is aimed at minimizing the

total investment cost of constructing new transmission lines and is given by

$$CI(X) = a \sum_{l \in \Omega} \sum_{k=1}^{K_1} h_{lk} \sum_{m=1}^{M_{lk}} X_{lkm} \quad (8)$$

where Ω is the subset of branches where new investment is allowed, a is the weighting factor for invest cost, $CI(X)$ is the total invest cost, h_{lk} is the invest cost of line and M_{lk} is the maximum number of new lines. Pereria and Pinto [159] and Bennon et al. [160] proposed sensitivity analysis methods for allocation of additional circuits to deal with the problems associated with overloads, load curtailment, susceptances reinforcement, etc. The procedure initiates with a solution and improves it in successive evaluations, until a quasioptimal solution is achieved. The major advantage of using sensitivity analysis is that the minimum load shedding and load supplying capability indices are able to convert the overloads into load curtailments, thereby providing consistent indices for integrated expansion planning of transmission and generation systems.

A single stage optimization method to develop a network expansion procedure using sensitivity analysis and the adjoint network approach was proposed by Ekwue and Cory [161]. The method employs a phase-shifting transformer to transfer power from a new generating station parallel to an existing line to a loaded AC system and enables control of network flows using steady-state conditions. Ekwue [162] presented an interactive simple heuristic method based on DC load flow approach which determines the number of lines of each specification to be added to a network to eliminate system overloads at minimum cost. The coherency approach is used to determine which lines should be augmented as a result of overloads in some lines. Static optimization based on the steepest-descent algorithm was performed to determine the new admittance to be implemented along these RoW. Similar interactive transmission planning methods based on DC load flow models are found in the literature. These methods primarily aim at determining the number of new line additions and then an optimization method or network synthesis algorithms are applied to achieve line additions at minimum cost [163–167].

Meta-heuristics is an iterative generation process which acts as a guide for its subordinate heuristics in order to efficiently find the optimum or near-optimum solutions of the optimization problem. Meta-heuristics made momentous progress in search methods which are successful in solving complex optimization problems in varied areas superior than their subsidiary heuristics. Algorithms that adopt meta-heuristics include simulated annealing (SA), genetic algorithms (GA), tabu search (TS), evolutionary algorithms/programming (EA/EP) and particle swarm optimization (PSO). Most of the meta-heuristic procedures are hybridized i.e combined with mathematical or other optimization procedures for solving real world problems. It should be noted, however that there are some theoretical convergences for some of the meta-heuristics under assumptions that cannot be satisfied in real world [168].

GA is a global search method based on natural selection mechanism and genetics. GA differs from conventional optimization techniques by using the concept of population genetics to guide the optimization search. GA searches from population to population instead of point-to-point search. A number of algorithms proposing GA for solving the transmission planning problem can be found in literature [169–184]. Rudnick et al. [169] and Asadzadeh et al. [170] proposed a dynamic transmission planning methodology using a genetic algorithm for determining an economically adapted electric transmission system in a deregulated open access environment. The objective function for providing transmission service at minimum cost is given by

$$\min\ F = \sum_{t=1}^{T} \left[C^{t}_{invest} + \sum_{i=1}^{N} (C^{ti}_{gen} + C^{ti}_{unser}) \right] \quad (9)$$

where t is the number of time periods, I is the number of buses, C^{t}_{invest} is the transmission investment costs, C^{ti}_{gen} is the generation variable cost and C^{ti}_{unser} is the annual unserved energy cost. An algorithm using short term marginal income sensitivity information is developed and applied to a long range economically adapted transmission grid required for indicative expansion plans and transmission pricing in deregulated open access system. An improved genetic algorithm was proposed by da Silva et al. [171] for transmission network expansion problem. The algorithm accounts for modifications made in the representation of fitness function, selection, crossover and mutation mechanisms which enables fine tuning of parameters capable of producing better quality solutions. Many other similar modifications made to GA are tested successfully on real time power systems with good convergence rates [172–174]. Yoshimoto et al. [175] and Escobar et al. [176] demonstrated hybrid GA, which is a combination of GA and other computing techniques applied to transmission network expansion problems. This hybrid GA exhibited the advantages of individual techniques while overcoming the drawbacks of each other on the final solution.

Abdullah et al. [178] presented an automated analysis and optimization procedure which integrates finite element analysis and numerical methods for computational analysis and weight optimization of transmission towers subjected to static loading. The finite element method is used to determine the stresses and displacements and a FORTRAN based GA was implemented to search for optimum designs. Jalilzadeh et al. [179] proposed a static transmission network expansion planning problem considering the voltage level of the transmission lines and the network loss using the genetic algorithms. Sadegheih and Drake [180] presented a method for analysis of minimum cost flow problem using genetic algorithms and simulated annealing. The minimum cost flow problem holds a central position among network optimization models because it has a wide range of applications and can be solved very efficiently. The model considers flow through a network with limited arc capacities, cost flow through an arc, multiple sources and destinations for the flow with associated costs and various junction points between the sources and destinations for this flow. The network problem can be formulated as a linear programming problem as shown in Eq. (10) and solved by a generalization of the transportation simplex which is highly efficient.

$$\min\ Z = \sum_{i=1}^{n} \sum_{j=1}^{n} Cost_{ij} X_{ij} \quad (10)$$

where X_{ij} is the power flow and $Cost_{ij}$ is the cost per unit power flow. Results indicated that genetic algorithms and simulated annealing are a feasible, robust and practical engineering tool for minimum cost flow problem.

Youssef [181] applied a constrained genetic algorithm for long range transmission planning problem which is capable of handling static and dynamic modes of system planning. The cost function consists of fixed costs, variable costs and a loss to be minimized subjected to system constraints and is represented by

$$\text{minimize}\ \ Cost = \sum_{i=1}^{N_t} \left[P^{i}_{0} E^{i} + \sum_{j=1}^{N_L} \sum_{k=1}^{N^{j}_{p}} \{ R^{i}_{j,k} \alpha^{i}_{j,k} + C^{i}_{j,k} \beta^{i}_{j,k} \} \right] \quad (11)$$

where N_t number of time planning periods, P^{i}_{0} is the total annual power loss, E^{i} is the present worth of energy loss cost per unit, N_L is the number of available right of ways, N^{j}_{p} is the number of permitted parallel paths in available right of way, $R^{i}_{j,k}$ is the present

worth of variable cost of line, $C^i_{j,k}$ is the present worth of installation cost of the line and $\alpha^i_{j,k}$, $\beta^i_{j,k}$ are the integer constants. The model was tested on an IEEE 6-bus test system which provided an accurate present worth of the transmission system considering change of parameters with time, according to inflation and interest rates. Analysis and optimization of multi-objective transmission network expansion planning problems implementing multi-objective GA were reported in the literature [182–184].

SA is an intelligent approach resulting in a good though not necessarily optimal solution, within a reasonable computation time. SA comes from analogy between the physical annealing of solid materials and optimization problem. SA simulates the cooling process of solid materials, known as annealing. The goal is to find the best arrangement of molecules that minimizes the energy of the system, which is referred to as the ground state of the solid material. SA algorithm was employed to solve the problems of combinatorial nature especially optimization of transmission network systems [185]. The method does not solve for any particular property of the problem, such as linearity or convexity, yet has the ability to provide solutions arbitrarily close to an optimum as cooling process slows down. However, the computational burden can be very high in some cases to find an optimal solution. Gallego et al. [186] presented a parallel simulated annealing approach to improve solution quality and decrease computational time. The SA optimization model is given by

$$\min \ Cost = \sum_{i,j} C_{ij} n_{ij} + \sum_i \alpha_i \gamma_i \tag{12}$$

where C_{ij} is the cost of addition of a line, n_{ij} is the number of lines to be added, α is the factor associated for loss of load caused by lack of transmission capacity and γ is the vector of virtual generation capacity. The method employs the division method for investigating the conditions under which parallel algorithms are most efficient.

Tabu search emerged as an efficient search paradigm for determining high quality solutions to transmission planning problems. The search is characterized by acquiring knowledge, and subsequently profiting from this knowledge. The drawback of this method is that the effectiveness depends on the strategy for tabu list manipulation. The know how to specify the size of the tabu list plays an important role in the searching process for a good solution [187]. The key advantages of SA and TS are their generality, ease of applicability and their ability to escape local optima.

EA are stochastic search methods aiming to find an acceptable solution where it is impractical to find the best one with other techniques. Ceilieno and Nieva [188] presented an evolutionary programming approach for optimizing a single stage transmission planning problem as given below

$$\min \ Z = \sum_{ij} C_{ij} n_{ij} + \sum_{k=1}^{ND} \left[\sum_{i=1}^{N} \alpha_i \gamma_{ik} + \sum_{i=1}^{N} c_{ge} g_{ik} \right] T_k \tag{13}$$

where C_{ij} is the cost of adding a line, n_{ij} is the number of existing lines, α_i is the value of loss load, γ_{ik} is the susceptances of line, c_{ge} is the cost of generation, g_{ik} is the generation capacity and T_k is the duration of demand condition. The method uses a stochastic procedure for creation of descendants which includes competition and performance based selection from a population of parents and children. The main advantage of this method is that, it does not require the genetic coding of decision variables as GA and produces extremely large number of alternative solutions for medium and large size electric systems. Sum Im et al. [189] proposed a differential evolutionary algorithm for dealing with static and multistage transmission expansion planning problems. The algorithm employs real coded variables and can directly operate on floating point numbers and depends on mutation operator for carrying out the search. The method was implemented on a wide range of low to high complex transmission network optimization problems and the results concluded that the best investment with low computational cost can be obtained. Combination of GA, SA, EA/EP and TS has been applied successfully to many complicated combinatorial nature optimization transmission planning problems [190–194].

PSO is the swarm intelligence method used to model social behavior for guiding swarms of particles towards the most promising regions of the search space. PSO was adopted by researchers for transmission planning problem [195–199] and resulted in fast convergence rates. Torres and Castro [195] implemented a parallel local PSO for solving the static transmission expansion problem consisting of expansion and operation subproblems. The objective function to be optimized is given by

$$\min \ v = \sum_{(k,\,l) \in \Omega} C_{kl} n_{kl} + w \tag{14}$$

$$\min \ w = \sum_{k \in A} \alpha_1 \gamma_{Pk} \tag{15}$$

where v is the total cost of expansion, w is the cost of operation, C_{kl} is the cost of adding a new line, n_{kl} is the number of lines in the available right of way, α_1 is the cost of load shedding and γ_{Pk} is the susceptances of the line. The model employs neighborhood concept to reduce the global information exchange scheme to a local one, where information is diffused to small parts of the swarm after each iteration. Information regarding the overall best position is initially communicated only to the neighborhood of the best particle and successively to the rest through their neighbors as each particle assumes a set of other particles to be its neighbors. Kamyab et al. [196] proposed a PSO for dealing with the multistage transmission expansion problems taking into account multiyear time horizon, scenarios based on the future demands of system, investment and operating costs, $N-1$ reliability criterion, and the continuous non-linear functions of market-driven generator offer and demand bids. The model uses a diversity controlled PSO to overcome the problem of premature convergence and a initial high diversity swarm to cover the search space efficiently.

Torres et al. [197] presented unified and evolutionary PSO algorithms for optimizing the transmission network expansion planning problem. The properties of exploration and exploitation are taken care by two variants of unified PSO i.e. the global variant, in which the entire swarm is considered as the neighborhood of each particle, and the local variant, where neighborhoods are strictly smaller. The global variant converges faster towards the overall best position than the local variant and stands out for its exploitation ability. The local variant has better exploration abilities, since information regarding the best position of each particle is gradually communicated to the other particles through their neighbors. Evolutionary PSO combines the advantages of evolutionary strategies and PSO (evolutionary and self-adaptive) acting in sequence, each one with its own probability of producing not only better individuals, but also a better average group. The algorithm depends on a set of particles that evolve in the search space trying to determine the optimal point in this space. Unlike PSO, the evolution not only looks at the behavior of particles but also in the weights that affect movement of these when they move forward in the search space. The main advantage is that it is a self-adaptive method, which automatically tunes its parameters or behaviors in order to produce an adequate rate of progress towards the optimum. The concept of discrete PSO and integer multiobjective PSO were presented by Shayeghi et al. [198] and Ayala et al. [199] respectively for application with transmission network expansion planning problems. The objective(s), advantages and disadvantages of the heuristic and meta-heuristic optimization methods are presented in Table 4.

5.3. Other promising optimization models

Even though the above mentioned optimization techniques are successful in dealing with transmission line planning problems, technical literature provides other promising techniques which can be used to find optimal solutions. Forghani et al. [200] developed a hybrid model with combined real GA associated with the goal attainment method (CORGA) and implemented on real time case study. The transmission line planning problem under deregulated environment is modeled as a constrained multi-objective optimization problem and effective solutions were obtained. Gheng et al. [201] proposed chaos optimal algorithm (COA) to solve transmission expansion planning problem considering transmission surplus capacity and load factor. The model aims to get the best distribution of branch load factors together with minimizing the investment simultaneously. Son et al. [202] presented the well-being method and the cost-optimization method to solve the transmission expansion planning problem which estimates the state probability by capability and calculate reliability of the system. Eghbal et al. [203] proposed a memtic meta-heuristic optimization technique known as shuffled frog leaping algorithm (SFLA) for modeling transmission planning as a mixed integer programming problem. The algorithm aims at minimizing the total cost by finding the place, number and type of new transmission lines required to ensure that the power system meets the forecasted demand in the most economic and reliable way. Zareian-jahromi et al. [204] proposed an algorithm based on game theory which comprises three optimization levels to determine Nash equilibrium such that the most profitable strategy for both sides of the game can be found out in an expansion planning game. Other methods employing game theory for solving transmission planning problems were discussed in the literature [205–207].

Pringles and Rueda [208] proposed a heuristic based mean variance mapping optimization (MVMO) and collaborative MVMO (CMVMO) for modeling the transmission line expansion planning as a mixed-integer nonlinear programming problem. The advantage of MVMO is that it uses a special mapping function for mutating the offspring on the basis of the statistics of the *n*-best population so far attained. The balance between search diversification and intensification allows MVMO to converge faster and find the optimum solution quickly with minimum risk of premature convergence. Rathore et al. [209] proposed a mosquito behavior based (MOX) evolutionary algorithm for finding an optimal solution to the transmission line planning problem in the static time horizon. The objective function consists of total transmission cost to be minimized by considering construction cost of each line and number of lines added in RoW as variables. MOX algorithm is on intelligent behavior of mosquitoes in their reproduction and early development stages and the position of an adult signifies a possible solution of the optimization problem.

Liete et al. [210] presented an ant colony based optimization approach for finding reliability worth for transmission planning problems. The model solves the multi-stage transmission planning problems by finding the best solutions for the last year of the planning horizon first and then assesses the corresponding solutions conditioned to the load levels of the preceding years. The aim is to coordinate the set of reinforcements achieved for the last year with those obtained with the preceding years and finally, the interruption costs associated with the coordinated solutions are evaluated and considered together with the investment costs for obtaining the optimal solution. Hinojosa et al. [211] proposed a simulated rebounding optimization algorithm for solving multi-stage security constrained transmission planning in power systems. The problem is formulated as large-scale, mixed-integer, non-linear programming problem employing a new constructive heuristic approach based on a local controlled random search was used to choose the decision variables. The model was implemented on Ecuadorian and Chilean power systems and the results indicated that the proposed approach is accurate and very efficient, and has the potential to be applied to real power system planning problems.

Rathore et al. [212] presented an artificial bee colony (ABC) algorithm based optimization approach for finding optimum solution for transmission planning problems. The problem is formulated based on lossless DC power flow model with the objective of minimizing the investment cost. ABC algorithm is meta-heuristic algorithm based on intelligent behavior of honey bee swarm and the position of a food source signifies a possible solution of the optimization problem. Binato et al. [213] proposed a greedy randomized adaptive search procedure (GRASP) for transmission expansion planning problems. The method is an expert iterative sampling technique consisting of construction phase and local search phases for every iteration. The construction phase finds a feasible solution for the problem and the local search phase seeks for improvements on construction phase solution. Verma et al. [214] proposed a harmony search technique based on the musical process of searching for a perfect state of harmony. The harmony in music is analogous to the optimization solution vector, and the musicians improvisations are analogous to local and global search schemes in optimization techniques. The algorithm is robust and computationally efficient compared to existing meta-heuristic techniques for solving the transmission expansion problem. The basic objective(s), the merits as well as the demerits of these optimization techniques are presented in Table 4.

Apart from the above discussed optimization algorithms essentially aimed at finding an optimum solution to the transmission planning problem, there are other interesting techniques and literature available for problems relating to transmission line issues. Song and Zheng [215] proposed three conductor selection methodologies viz. the conductor economical current density method, the fever condition method and the voltage loss condition method for selecting suitable conductor size which helps in energy saving and conservation in transmission grids. Lotfjou et al. [216] presented a stochastic simulation based mixed integer linear programming transmission expansion problem considering random generator outages, AC/DC transmission lines and load forecast errors. The model helps in selecting the optimal set of AC/DC transmission lines to meet the transmission planning criteria. Eghbal et al. [217] presented a PSO based algorithm for optimal voltage and conductor bundle selection in transmission lines. Fuzzy logic based tools are used for obtaining optimum transmission tower configurations by Rao [218]. Tran et al. [219] proposed a fuzzy integer programming based method for transmission expansion problem considering the permissibility and ambiguity of the capital cost for constructing the new transmission lines and reliability criteria of the system. Research has been performed on transmission planning using object oriented software [220] and expert systems [221–224]. A comparison of various optimization techniques available in literature for transmission planning was performed by Padiyar and Shanbhag [225], Sadegheih [226,227], Gallego et al. [228] and Romero and Monticelli [229].

6. Economic analysis

Electricity sector significantly influences national economy, as investments made in this sector are huge and constitute a major portion of the nation's total investment. In contrast to the vertically integrated electricity market serving the consumers energy needs directly by a regulated utility, the power system is undergoing restructuring due to introduction of deregulation. This necessitates power utilities, especially in the transmission sector, to improve existing facilities and construct new lines for

accommodating the dynamic changes caused by open access and maintain stability of the system. This process involves huge investment which needs to be technically and economically justified before execution. Transmission system management involves decision making at various stages based on tangible and intangible benefits. Tangible benefits can be transformed into costs while the latter cannot. Economic analysis considers these intangible benefits into consideration along with tangible benefits in evaluating the various alternatives and helps in decision making process [230].

Simple methods of economic analysis include calculation of payback time and return on investment. Methods and procedures applicable for more extensive situations involving comprehensive economic analysis are life cycle costing, net present value analysis and discounted cash flow rate of return [231]. Life cycle costing is the most popular and widely adopted method by utilities in accessing the capital investment for transmission lines. Life cycle costing is the process of economic analysis to assess the cumulative cost of a project over its lifetime. The objective of life cycle costing is to provide information useful for decision making in any or all phases of a project's life cycle [232]. Lifecycle analysis starts with production of the technology passing through the entire useful life of the product to its recycling or disposal, while considering impacts on the economy, health and safety, the natural environment, and other elements of the public [233,234].

Jeromin et al. [235,236] developed a method for life cycle cost (LCC) analysis of a complete transmission system depicting the main cost influencing and important elements of the system, for examining diverse maintenance strategies with regard to their corresponding life cycle costs. Present value of the system is determined considering useful lifetime of equipment, outage costs, maintenance costs, maintenance interval, calculation time and penalty. It was observed that penalty factor determines the incentive for maintenance and renewal activities. When penalties were applied, outage costs reflect the shares of equipment groups on non-delivered energy and when no penalties were applied, outage costs approximately reflect the respective shares on interruption frequency. The authors concluded that life cycle cost analysis is useful for considering changes in the finance sector or induced by regulation and it is possible to customize the maintenance strategies to these new conditions. Liu et al. [237] found that the present process of cost management is narrow and limited in application as this is done without considering costs due to power loss, maintenance and fault loss. A study was conducted on life cycle cost of transmission line whose objective of selecting conductor type depends on investment cost, operation wastage cost, maintenance cost, fault loss cost and retirement cost. The model used for economic analysis is given by

$$LCC = IC + OC + MC + FC + DC \tag{16}$$

where LCC is the life cycle cost, IC, OC, MC, FC and DC are the investment, operation, maintenance, failure and disposal costs respectively. The authors concluded that life cycle cost depends on cost comparison between alternatives and its main function is to design a cost assessment methodology, analysis of investment efficiency and play a reference role on the decision making.

Grant and Longo [238] presented a methodology based on economic analysis, for conductor selection based on PWRR for EHV lines. PWRR is the sum of the present worth of levelized annual fixed charges on the total line capital investment, plus annual expenses for line losses as shown

$$PWRR = \sum_{n=1}^{NYE} \left(1+\frac{i}{100}\right)^{-n} \left(CI\frac{F_L}{100} + ADC_n + AEC_n\right) \tag{17}$$

where $PWRR$ is the present worth of revenue required, NYE is the number of years to be studied, n is the nth year, i is the annual discount rate in percent, CI is the total per mile capital investment, F_L is the line fixed charge rate in percent, ADC_n is the per mile demand charge for line losses for year n and AEC_n is the per mile energy charge for line losses for year n. The cost of line losses is based on the cost of generating the losses. Annual demand and energy charges are calculated as shown below.

Annual demand charge for line losses for year n

$$ADC_n = \frac{C_{kW}\, ESC_n}{10^3}\, \frac{F_g}{100} \left(1+\frac{RES}{100} I_L^2 \frac{R}{N_C} N_{ckt}\, N_p\right) \tag{18}$$

where ADC_n is the annual demand charge for year n, C_{kW} is the installed generation cost, ESC_n is the escalation cost factor for year n, F_g is the generation fixed charge rate in percent, RES is the required generation reserve in percent, I_L is the demand phase current in amperes per circuit, R is the single conductor resistance in ohms per mile, N_C is the number of conductors per phase, N_{ckt} is the number of circuits and N_p is the number of phases.

Annual energy charge losses for year n

$$AEC_n = \frac{C_{MWh} ESC_n}{10^6}\, 8760\, \frac{L_f}{100} \left(I_L^2 \frac{R}{N_C} N_{ckt}\, N_p\right) \tag{19}$$

where AEC_n is the annual energy charges for year n, C_{MWh} is the cost of generating energy in Rs/MWh, ESC_n is the escalation cost factor for year n, L_f is the loss factor for determining energy losses in percent, I_L is the demand phase current in amps per circuit, R is the single conductor resistance in ohms per mile, N_c is the number of conductors per phase, N_{ckt} is the number of circuits and N_p is the number of phases.Escalation cost factor for year n

$$ESC_n = \left(1+\frac{E_f}{100}\right)^{n-1} \tag{20}$$

where ESC_n is the escalation cost factor for year n and E_f is the escalation rate in percent. In the era of increasingly higher transmission voltages, it is concluded that larger conductors economically justify the investment costs over the operating life of the transmission line.

Beglari and Laughton [239] proposed a linear programming based combined cost model for economic planning of generation and transmission systems. Unlike in other optimal planning methods which incorporate operating constraints into linear programming models to interpret the operating conditions, the operating constraints are removed from the mathematical model in this proposed method. The model assumes possible plant operating conditions and corrective measures for these assumptions were done by optimizing around the choice of the investment plan along with assumptions. The method was found helpful in planning of large thermal systems and hydro-thermal systems. Baughman and Bottaro [240] presented a regression based economic analysis method to estimate the cost of T&D system by dividing it into categories based on the equipment ratings. David et al. [241] presented a translog/structural cost model including technical and economic variables for examining the existence of economies of scale in electric transmission service. The model examines the relationship between average variable costs and capacity utilization of the transmission system. This model is helpful in defining the use of transmission capacity measures and provides a methodology for measuring cost characteristics. The model was tested with the data provided by Department of Energy, USA and the results indicated that a number of the relevant variables in the model are statistically significant and influences the total costs. The translog cost model can be used to predict the costs of transmission system based on capacity utilization.

Sohtaoglu [242,243] presented a method to evaluate the effects of economic parameters on the power transmission expansion planning and uncertainties associated with capital costs. The

Table 5
Comparison of various economic analysis methods.

S No	Objective/problem	Method/ technique	Components of cost model	Input parameters	Remarks	References
1	LCC evaluation of 110 kV transmission grid with air insulated substations	Present value analysis	Investment, operating and recycling costs	Equipment, operation and maintenance costs	– Cost of non-delivered and loss of sales not included – Changes in interest and inflation rates are separately examined	[235,236]
2	LCC analysis of power transmission lines	Present and final value analysis	Repeated costs and Non repeated costs	Investment, operation, maintenance, failure and disposal costs.	– Sensitivity analysis was not performed to examine the changes in input economic parameters	[237]
3	Economic analysis of EHV lines	PWRR method	Investment cost, Annual demand and energy charges for line losses	Installed generation cost, loss factor, escalation factor	– Concludes that cost of losses justify the use of larger conductor size in EHV lines – Sensitivity is explored with respect to switching surge requirements.	[238]
4	Economic planning of generation and transmission systems	Combined costs method	Present valued costs	Capital costs, fixed charges per unit, operating costs	– Accounts for economic size of the unit – Operating constraints are removed from the mathematical model – Suitable assumptions are made initially regarding operating conditions and investment plans	[239]
5	Allocation of T&D costs to consumers	Regression analysis	Installation, operation and Maintenance costs	Cost of T&D lines and Substations, O & M costs	– Transmission and distribution expenses were separately calculated – Capital investment is converted into annual capital charge – General expenses are calculated for T&D system and average charge is levied to customers	[240]
6	Investigate the existence of capacity and economies in transmission	Translog/ structural cost model	Average variable costs and capacity utilization of the transmission system	Equipment capacity, power flows, Transmission costs, Line length	– R-square statistic indicated 79% accuracy of the model in detecting cost variations – Equation for economies of scale has been formulated – Positive and negative of the equation indicate economies and diseconomies of scale in transmission.	[241]
7	Investigate the effect of differing investment programs and macroeconomic parameters on transmission planning	Present and future worth model	Capital cost, variable cost, power loss cost.	Interest rate, inflation rate, discount rate, future cash flows.	– Time value of money is taken into account for evaluating investments – Cash flows are modeled as uniform, linear gradient and geometric gradients for analyzing fixed capital investment.	[242,243]
8	LCC analysis of sub-transmission networks	Net present value analysis	Capital Investment cost, O&M cost, cost of losses	Equipment, operation and maintenance costs	– Determination of production price indexes and discounted borrowing – Rates over the life of the line for analysis purposes – Sensitivity analysis is to be performed based on the key performance indicators	[244]
9	LCC of planning and design of ± 660 kV DC transmission lines	Net present value analysis	Fixed and variable costs	Investment, operation, maintenance, failure and waste costs	– Difference between net present value is reflected in the life cycle of energy-saving profitability of dynamic evaluation index – LCC analysis is applied for engineering design and management.	[245]
10	Economic benefit comparison between series FACTS device installation and new transmission line investment	Probabilistic method	Investment cost, energy generation bid cost	Load pattern probability, equipment availability, capacity of new line and FACTS equipment	– Probabilistic method was used for evaluation of equipment availability and load variations while energy generation bid cost and investment cost have been used for the economic evaluation.	[248]
11	Utility economic analysis problem	Interval analysis	Initial investment cost, operating cost	Interest rate, inflation rate, taxes rate and credits	– Revenue requirement is computed in interval form capable of dealing with uncertainties – Sensitivity analysis can be carried out along with normal computations varying all the cost driving parameters at a time.	[249]

effects of different investment programs and macroeconomic parameters such as interest rate and inflation rate on long term power transmission system expansion planning are investigated. Jordan [244] proposed a conductor/structure optimization method based on life cycle cost analysis for the decision-making processes for sub-transmission line projects, especially in cases where the return on investment is low. Sauma and Oren [245] proposed a methodology for electricity transmission investment assessment which is capable of evaluating the economic impacts on the various effected stakeholders and account for strategic responses that could enhance or impede the investment's objectives. Huan et al. [246] presented an economy evaluation method for planning and design of HVDC systems by using the life cycle cost (LCC) method to find the converging points of the economy and reliability.

Awad et al. [247] proposed a model for economic benefit assessment in upgrading transmission lines in restructured environment. The network is modeled as a linear programming problem considering market uncertainties for maximization of profit. Attaviriyanupap and Yokoyama [248] proposed a probabilistic method to compare the economic benefits evaluating from installing a new transmission line and series FACTS device in a deregulated power system. The application of interval mathematics for dealing with uncertainties in planning, design and operation of transmission lines was reported in the literature [249–253]. Interval mathematics is capable of providing a range of solution based on economic factors and helps to deal uncertainty effectively. Mathews et al. [249] presented a utility economic analysis based on interval mathematics for determining the cumulative PWRR and breakeven point for the two alternatives considered. The major advantage of this method is that it allows sensitivity analysis to be carried out simultaneously along with normal calculations considering all parameters to be varied simultaneously so that the impact of these variations can be easily analyzed. Results are presented in an interval form providing insights into the effects of parameter uncertainties on the outcome of utility economic analysis. Shaalan [253] presented a methodology for transmission line analysis using interval mathematics. This model incorporates “Unknown but Bounded” in which upper and lower limits on the uncertainties are assumed without probability distributions. The calculation of sag and inductance for transmission line was carried out to demonstrate the methodology. Sag calculations are performed to determine the change in cable length, given a fixed span and an interval of cable sag values, for numerous variations in temperature. The resulting change in cable length will therefore be an interval corresponding to the interval of cable sag values. Similar analysis was performed to determine inductance values. A comparison of the various economic analysis methods has been presented in Table 5.

7. Observations and recommendations

Based on the review presented in this study, it is observed that classical optimization models have limited application for real world problems. Heuristic and meta-heuristic optimization models have wide acceptance in solving engineering optimization problems, but not without limitations. The common drawbacks include lack of a comprehensive model, dependence of solution quality on initial parameter settings and trapping in local optima [254]. In the present review on optimal economic planning of transmission lines, it has been observed that there is no guaranteed convergence and user interaction in the proposed mathematical models. The models are intractable and require long computational times. The requirement of large number of decision variables limits the scope of applying mathematical models for transmission line optimization problems. It has also been observed that most of the research in transmission planning was concentrated on static models which do not consider the different time frames in constructing and operating a transmission line which is dynamic in nature. Also, resistance power losses are not considered in the proposed algorithms. In contrast to mathematical models, heuristic methods need lesser computational times as compared to mathematical methods and yield a good, but not necessarily optimum solution and hence, provide an effective alternative for solving transmission planning problems.

The above observations infer that there is a need and scope for improvement of the models used for the development of optimal economic planning of power transmission lines. Options like redesigning and rearranging should be taken into account by the models in addition to line additions. Dynamic models involving multiple time frames for construction and operation of lines need to be considered in transmission planning. Costs, other than capital investment, such as operating and outage costs are to be considered in mathematical modeling and economic analysis methods. Models capable of handling multiple contingencies, energy demand changes during planning period, exact time for installing new lines, etc. are to be developed. In the present power system scenario, where deregulation and stringent environmental/regulatory norms introduce high level of uncertainties in the power sector, there is a need for development of algorithms competent of dealing with realistic integrated AC Power flow models with uncertainties. Transmission system pricing is a prominent issue attracting many power professionals and researchers, especially during the recent times when open access has been introduced. Several serious and contradictory issues came into picture in pricing transmission system usage due to open access in transmission systems. In this regard, research work is required in the area of establishing relationship between transmission planning and transmission pricing capable of addressing the pricing issues.

8. Conclusions

In the present study, an attempt has been made to review the relevant aspects related to optimal economic planning of power transmission lines. The study evolves basics of transmission line planning and construction; current trends, challenges and possible solutions for the development of transmission lines; optimizations techniques/methodologies used in transmission planning. This paper also reviewed the economic analysis procedures for arriving at the overall cost occurring over the operating lifetime of the line which helps in effective decision making. The various methodologies adopted in transmission planning by earlier researchers revealed that, finding a global optimal solution for transmission line optimization problems is a complex task, particularly when many local optimal solutions exist. The fundamental conflict between accuracy, computational time and reliability is always present in these types of problems. A trade-off has to be made with these parameters, to arrive at the solution for optimizing the objective function satisfying constraints. A more efficient and reliable optimal solution can be obtained by hybrid approach which combines two or more optimization techniques. This helps individual techniques to combine their strengths and overcome each other's limitations in determining the optimal solution. The uncertainties involved in transmission line planning, construction and operation become larger and larger, especially in the era of deregulation and stringent environmental restrictions. Hence, novel comprehensive methods for design, planning, optimization and economic analysis need to be developed to analyze and to

foresee the technical and economic benefits resulting from new transmission lines.

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